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Analysis and Design of Ballastless Track Slab

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***Abstract:* This Paper presents the Analysis and Design of Ballastless Track Slab for 17t railway loading. Ballastless Track Slab is a continuous slab of concrete in which the rails are supported directly on the upper surface by using resilient pad. The aim of this paper is to analyse a ballastless standard rail track using STAAD Pro and to obtain maximum design moments as contours from STAAD Pro. The obtained moments are interpreted and used in design of transverse and longitudinal reinforcements for the track slab with respective to Indian Standards.**

***Keywords*: Ballastless Track Slab, Design Moments, Loads and Combinations, Reinforcement Design, STAAD Pro Analysis.**

I. INTRODUCTION

Presently all over the world ballastless track concepts are in practice, although at a moderate volume. The pattern of slab track use seems to rise by the time due to the higher demands for high speed railways and heavy freight trains. The slab may be cast-in-situ, resulting in a continuous length of concrete, or it may be constructed in discrete precast sections laid end to end. The main advantages of such structures are:

(i) Lower maintenance requirements
(ii) Increased service life of the track
(iii) No track maintenance like tamping and aligning
(iv) No problems with churning of ballast particles at high-speed
(v) Very high lateral and longitudinal track stability.

Xueyietal (2011) presented the design theories of the ballastless track in the world. The calculation methods and parameters concerning train load, thermal effect of high-speed railway ballastless track, together with the structural design methods are summarized. Steenbergenetal (2007) studied that by increasing the width or/and by applying eccentric reinforcement in the concrete bearing layer (CBL), a significant amount of soil treatment can be avoided. The increased stiffness of the slab track in many cases can replace the need of massive soil improvements when slab track is applied in earth structures, making it economically competitive comparing to the ballasted track. According to ESVELD and MARKINE (2009), the Slab track can be constructed in three ways:

(a) Using a slab with reinforcement at the neutral line. Since the bending stiffness of such slab is very poor massive soil improvements are required which makes such slab structure financially less attractive. (b) Using a slab with reinforcement at the top and at the bottom of the slab, this improves the bending strength of the track structure. (c) Using bridge or bridge like structures as a substructure in slab track design. The influence of bending of the bridge has a restricted influence on the bending stresses in the track slab. The principles of slab track concept along with the longitudinal and transverse reinforcement details are shown in Figure 1.

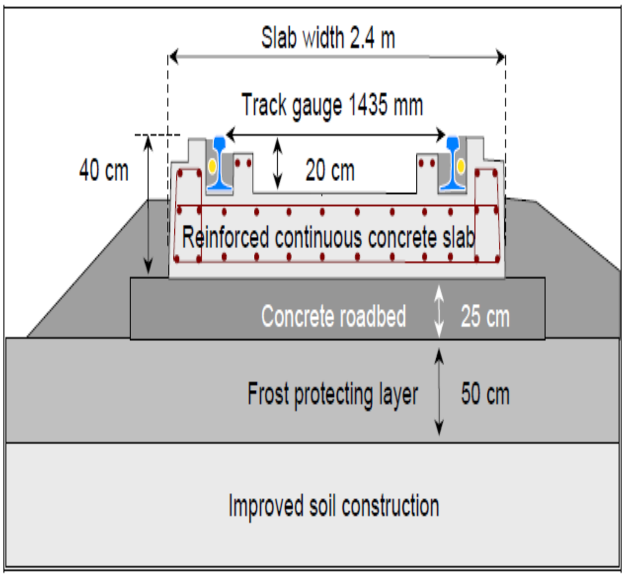

Fig. 1 Track slab concept (Coenraad ESVELD, 2011)

Georgios Michas (2012) discussed various non-ballasted concepts and some considerations are made in relation to life cycle cost for high speed track. He proposed that slab track is in a long-term perspective, more economically efficient as shown in Figure 2. Even though the slab track construction costs are 30 % to 50 % higher than the standard ballasted track, the maintenance costs for slab track are one-fourth of those for ballasted track.

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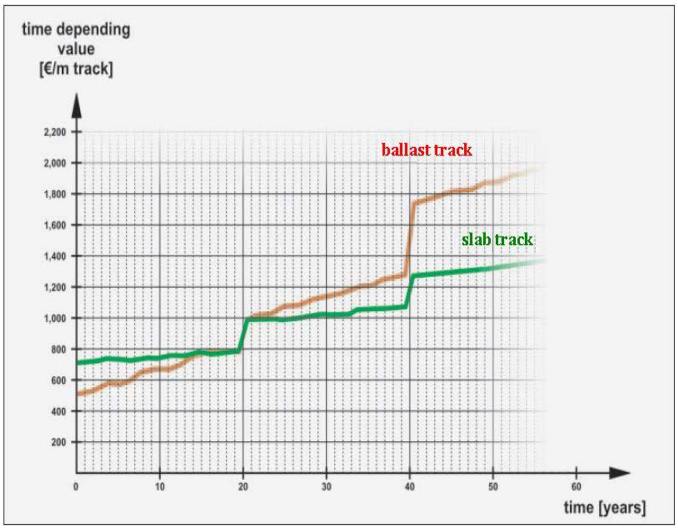

Fig. 2 Time depending value, ballasted track and slab track (Rudolf&Dirk, 2012)

II. MATERIALS AND COMPONENTS OF SLAB TRACK

The two main components of the track slab are the running rail and the fastening system. The typical track slab structure is shown in Figure 3.

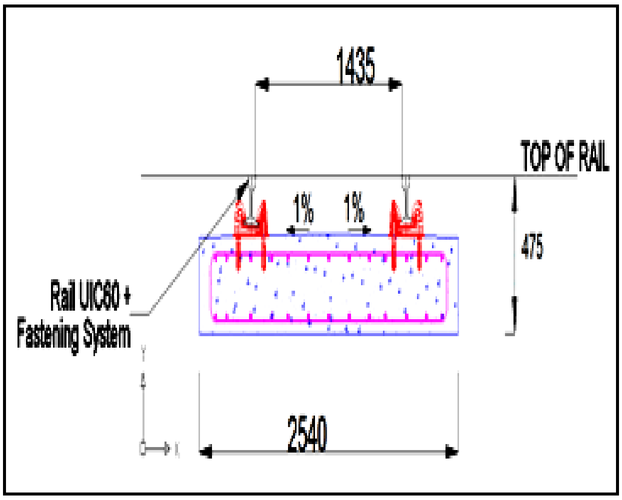

Fig. 3 Typical track slab structure

Rails are the horizontal member running throughout the track which is supported by the fastening systems. Figure 4 shows the Profile UIC60 in accordance with IRS-T12. The height of the UIC60 type rail system is 172 mm. The mass and section of the rail is 60.34 kg/m and 7686 mm^2.

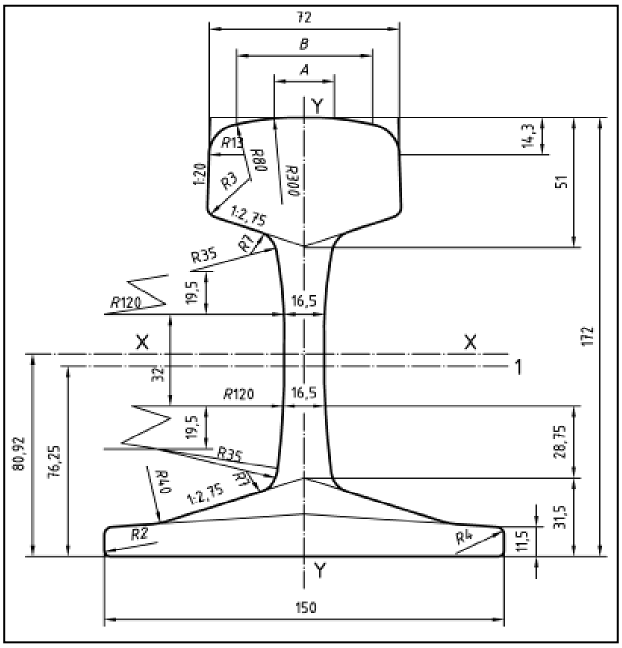

Fig. 4 Example of rail profile UIC60 with measurements (IRS - T12)

Fastening system is used to hold the rail element with the slab element. The fastening system shall have 4 anchor bolts at each rail seat. The spacing between each fastener is 0.65 m, in straight alignment as well as curves. The approximated weight of a fastener is 20 kg per fastening system. The maximal longitudinal restraint per fastening system is 13 kN.

III. SLAB TRACK MODEL

The aim of this chapter is to develop a model of a slab track using STAAD Pro software in order to perform an analysis under various loading conditions. The thickness of the slab was taken as 0.265 m.

A. Support Conditions

The ballastless track consists of a continuous slab of concrete where rails are supported on the upper surface of the slab. The support spring stiffness representing Hydraulic Bounding Layer (HBL) is taken with corresponding to the maximum tolerable deflection of 5mm. The maximum axle load of 170 kN is considered. The spring stiffness for the rail with respect to the fastening system of 26 kN/mm is applied throughout the running beam element and the stiffness 34 kN/mm for slab with respect to HBL is acting throughout the plate element. The slab track model under support conditions is shown in Figure 5.

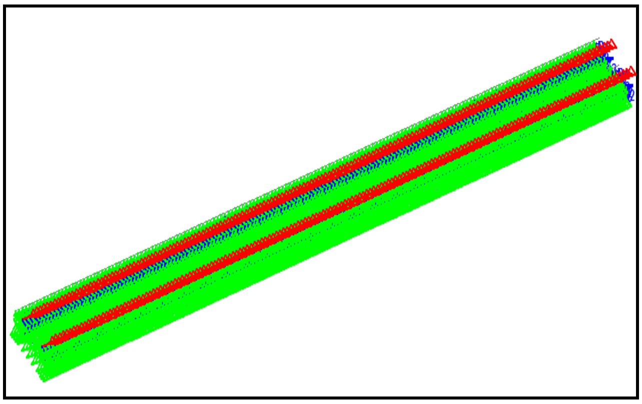

Fig. 5 Slab Track model under support conditions

B. Load Calculations

The loads to be taken into account in the slab track modelling are presented in the following sections and the loads summary is shown in Table 1. Some of them are applied vertically to the structure, other horizontally. The axis (X, Y, Z) are shown in Figure 6.

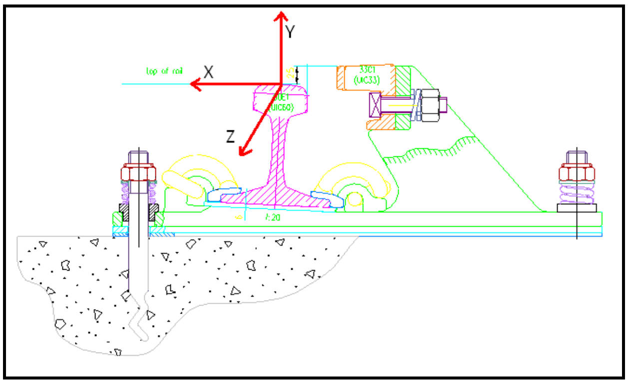

Fig. 6 Axis convention at the top of rail

The various types of horizontal and vertical loads acting on the structure are:

i) Dead Load (DL)
ii) Super Imposed Dead Load (SIDL)
iii) Live Load (LL)
iv) Dynamic / Impact Load (IL)
v) Lurching Force (LF)
vi) Earthquake Load (EQ)
vii) Traction & Braking Load (T&B)
viii) Racking Force (RF)
ix) LWR (Long Welded Rail)
x) Temperature (TR)

As per EN code, vertical wheel loads are distributed to fasteners under load at 50 % and to adjacent fasteners at 25 %. Horizontal wheel loads are distributed to fasteners under load at 70 % and to adjacent fasteners at 18 %.
The diagrammatic representation of the bogie details are shown in Figure 7.

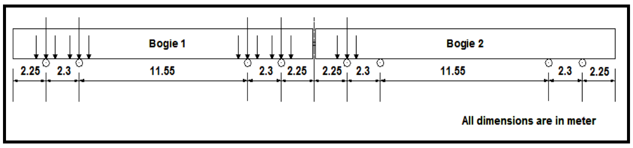

Fig. 7 Diagrammatic representation of bogie details

1) *Dead Load*: This is the self-weight of the track structure, mainly reinforced concrete which is given by its volumetric weight.

DL = Track width*Thickness*Volumetric Concrete
= 2.54*0.265*24
= 16.15 kN/m

2) *Super Imposed Dead Load:* SIDL is considered for the running rail portion.

SIDL = Rail/fastener + Fastening system load/fastener
= 0.6 + (0.2/0.6) = 0.93 kN/m

3) *Live Load:* According to the axle load value at the maximum capacity, as per EN Code, the train live load is LL=170 kN. LL per wheel is 85 kN.

4) *Impact Load:* As per Modern Railway Track by Coenraad Esveld, the impact load is dependent of the train speed and train quality. The dynamic factor can therefore b calculated by Eisenmann formula:

$$\gamma_{dyn} = t \cdot \varphi \cdot \left(1 + \frac{V-60}{140}\right) = 2 * 0.2 * \left(1 + \frac{80-60}{140}\right) = 0.46$$

Impact Load = Dynamic factor * LL
= 0.46 * 85 = 39.1 kN/wheel

5) *Racking Force:* Racking force is a nose force which is produced due to the lateral movement. The nosing force shall be acting horizontally at the top of the rails, perpendicular to the centre-line of track. It shall be applied on both straight track and curved track.

As per IRS Bridge Rules, the racking force is considered as 5.88 kN/m. Racking force per fastener is given by,

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Racking Force = 5.88*0.65 = 3.82 kN/fastener

6) *Traction & Braking Force:* Traction and braking force is frictional force acting between the rails and the trails. It is a longitudinal force of 18 % of the live load.

T&B Force = 0.18*85 = 15.3 kN/wheel

7) *Lurching Force:* Lurching forces are caused by the train rotating slightly about its axis. This causes a moment at rail level corresponding to 6 % of the maximum axle load multiplied by the distance between rails.

Lurching Force = (0.60*170)*1.507 = 15.37 kN/wheel

8) *LWR Load:* LWR load is a part of the rail steel expansion from rail to fastener to slab. The maximum longitudinal force induced on slab by the LWR force is limited to the longitudinal restraint capacity of the fastening system which is LWR = 13 kN/m. LWR per fastener is,

LWR = 13/0.65 = 20 kN/fastener

9) *Earthquake Load:* As per IRS Bridge Rules the seismic force shall be resisted is computed as follows. This force should be considered on both vertical and horizontal direction.

Earthquake Force,

Horizontal Force = $W_m * a_h$

= 85 * 0.09

= 7.65 kN/wheel

Vertical Force = 7.65*(1.81/1.51)

= 9.27 kN/wheel

TABLE I:LOAD SUMMARY

Types of	Symbol	Description	Distribution of Loads (kN/fastener)	
Loads			**Horizontal Loads**	**Vertical Loads**
Dead Load	DL	Self weight of track concrete	16.15 kN/m	
	SIDL	Self weight of track material	-	0.93 kN/m
Live Load	LL	Live Load	-	85
	IL	Impact Load	-	39.10
	RF	Racking Force	3.82	-
	T&B	Traction & Braking Force	15.30	-
	LF	Lurching Force	-	15.37
Other Loads	LWR	LWR Load	20	-
	EQ	Earthquake	9.27	7.65
	TR	Temperature	15	

C. *Load Combinations*

The following load combinations LC1, LC2 & LC3 are proposed for track structures based on realistic configurations for a track structure. The factors are inspired from IRS Concrete Bridge Code.

- LC1: Loads combination for normal condition
- LC2: Earthquake with Live Load condition
- LC3: Loads combination with Temperature and LWR forces.

The loads to be taken in each combination with appropriate load factors are shown in Table 2.

TABLE 2
LOADS TO BE TAKEN IN EACH COMBINATION WITH APPROPRIATE LOAD FACTORS

Loads	**Limit state**	**Load factors**		
		LC1	**LC2**	**LC3**
Dead Load	ULS	1.25	1.25	1.25
	SLS	1	1	1
SIDL	ULS	2	2	2
	SLS	1.2	1.2	1.2
Live Load Traction & Braking Lurching Racking	ULS	1.75	1.4	1.4
	SLS	1	1	1
Earthquake Load	ULS		1.25	
	SLS		1	
LWR	ULS			1.5
	SLS			1
Temperature	ULS			1.5
	SLS			1

The load combinations considered for the analysis are,

- 1.25DL + 2SIDL + 1.75*(RF+LF+T&B+LL+IL)
- 1.25DL + 2SIDL + 1.4*(RF+LF+T&B+LL+IL) + 1.25EQ

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- 1.25DL + 2SIDL + 1.4*(RF+LF+T&B+LL+IL) + 1.5LWR + 1.5TR
- 1DL + 1.2SIDL + 1*(RF+LF+T&B+LL+IL)
- 1DL + 1.2SIDL + 1*(RF+LF+T&B+LL+IL) + 1EQ
- 1DL + 1.2SIDL + 1*(RF+LF+T&B+LL+IL) + 1LWR + 1TR
- 1DL + 1SIDL
- 1DL + 1SIDL + 1T&B + 1LL + 1IL
- 1LL + 1IL + 1 TR

D. Staad Results

STAAD model is analysed with above conditions and results obtained are figured below. The isometric view of the model is shown in Figure 8.

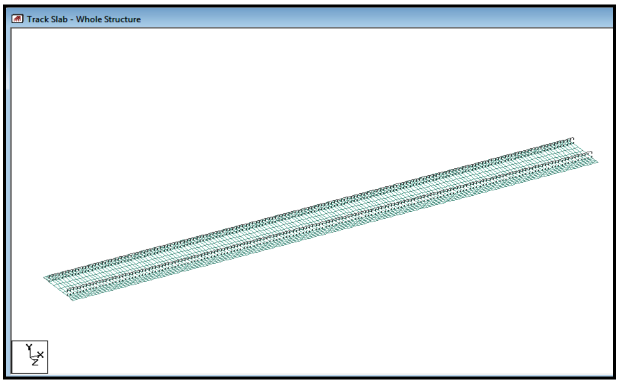

Fig. 8 Isometric view of the model

The following Figures 9 and 10 are showing the model of track slab under various loading conditions.

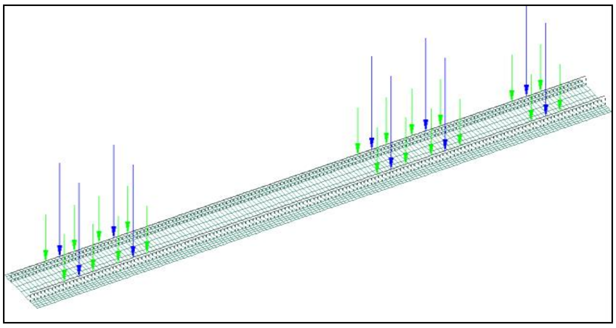

Fig. 9 Model with live loads

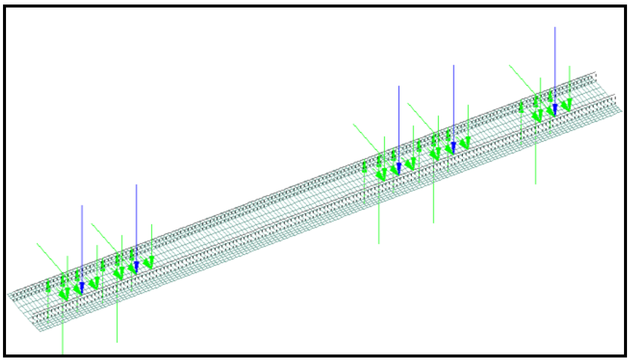

Fig. 10 Model with seismic load

The track slab shall be modelled for all combination of vertical loads and horizontal forces in SLS & ULS conditions and the model are shown in following figures. Figures 11(a) and 11(b) show the stress contour with load combinations of 1.25DL + 2SIDL + 1.75*(RF+LF+T&B+LL+IL) in X and Z direction respectively.

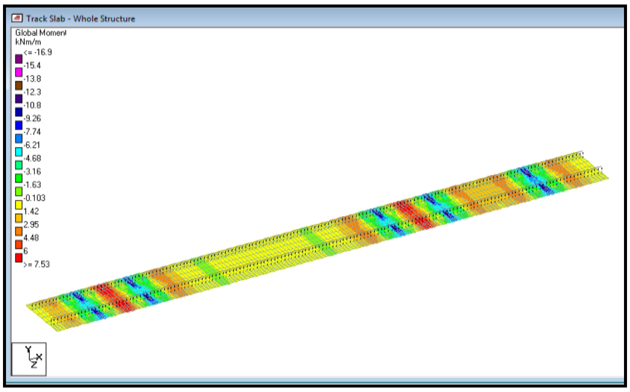

Fig. 11(a) Stress contour in X-direction

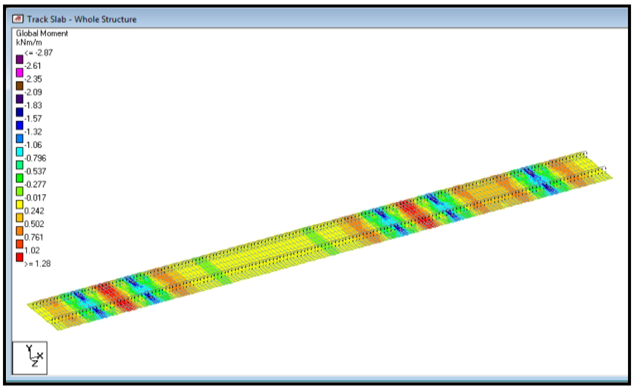

Fig. 11(b) Stress contour in Z-direction

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Figures 12(a) and 12(b) show the stress contour in X and Z direction respectively with load combinations of 1.25DL + 2SIDL + (1.4*(RF+LF+T/B+LL+I)) + 1.25EQ.

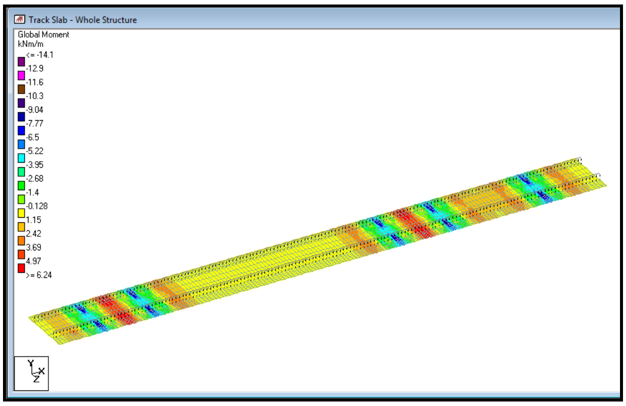

Fig. 12(a) Stress contour in X-direction

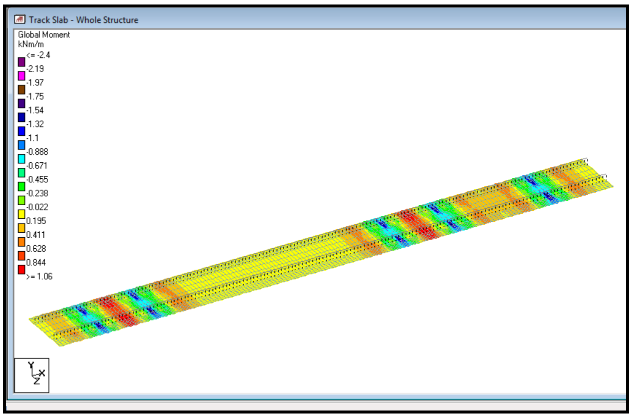

Fig. 12(b) Stress contour in Z-direction

Figures 13(a) and 13(b) show the stress contour in X and Z direction respectively with load combinations of 1.25DL + 2SIDL + (1.4*(RF+LF+T/B+LL+I)) + 1.5LWR + 1.5TR.

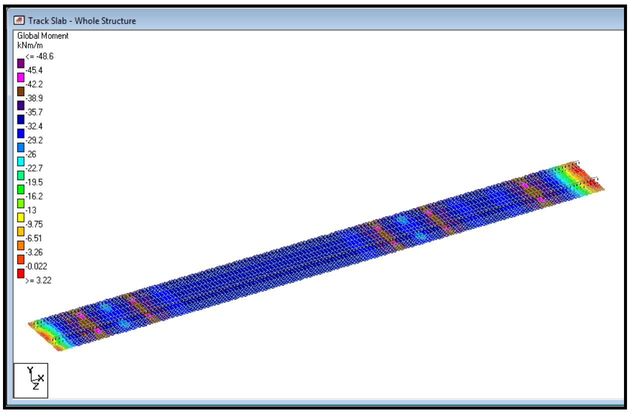

Fig. 13(a) Stress contour in X-direction

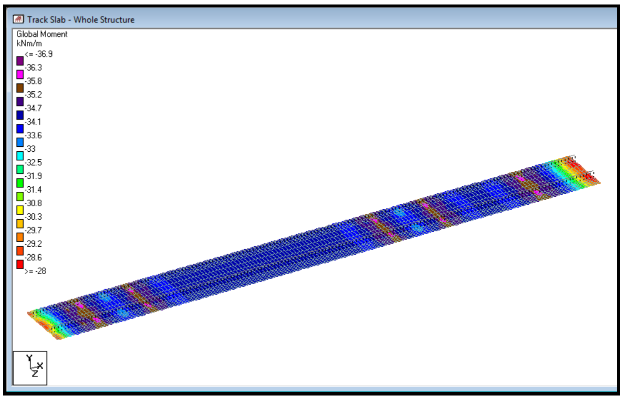

Fig. 13(b) Stress contour in Z-direction

E. Moments Summary

The sagging and hogging moments are obtained from the ultimate loading combinations as shown in Table 2:

TABLE 2
MOMENTS SUMMARY

LC	Moments in X-direction (kN-m)		Moments in Z-direction (kN-m)	
	Sagging Moments	Hogging Moments	Sagging Moments	Hogging Moments
LC1	16.90	7.53	2.87	1.28
LC2	14.10	6.24	2.40	1.06
LC3	48.60	3.22	36.90	28.00

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F. Design Moments

The maximum sagging and hogging moments in both X and Z direction are taken from the global moments which are shown in Table 3 and then these moments are used for designing the longitudinal and transverse reinforcements.

TABLE 3
DESIGN MOMENTS

Design moments (kN-m)	Sagging Moments	Hogging Moments
Mx (Longitudinal)	48.60	7.53
Mz (Transverse)	36.90	28.00

IV. TRACK SLAB DESIGN

The purpose of this calculation is to design the reinforcement required in concrete track slab:

(i) Longitudinal reinforcement in track slab
(ii) Transverse reinforcement in track slab

The calculations will be carried out with respect to the requirements of the Indian Standards for Serviceability Limit State (SLS) and for Ultimate Limit State (ULS). The reinforcement details are as follows:

Grade of steel	fy	=	500	Mpa
Grade of concrete	fck	=	35	Mpa
Width of Section	b	=	1000	mm
Depth of Section (End section)	D	=	265	mm
(Mid section)	Dm	=	265	mm
Max. dia bar provided	dx	=	12	mm
	dz	=	12	mm
Clear cover bottom reinforcement	Cb	=	50	mm
Clear cover top reinforcement	Ct	=	50	mm

Effective depth of section:

Bottom Reinforcement = D-Cb-(dx/2)
= 265-50-(12/2) = 209 mm

Top Reinforcement = D-Cb-(dx/2)
= 265-50-(12/2) = 209 mm

Bottom Reinforcement = Dm-Cb-dz-(dx/2)
= 265-50-12-(12/2) = 197 mm

Top Reinforcement = Dm-Cb-dz-(dx/2)
= 265-50-12-(12/2) = 197 mm

Limiting sagging moment, Mx (Bot) = 48.60 kN-m
Limiting hogging moment, Mx (Top) = 7.53 kN-m
Limiting sagging moment, Mz (Bot) = 36.90 kN-m
Limiting hogging moment, Mz (Top) = 28.00 kN-m

Depth check for moment resistance:
From IS456 for Fe500,

$x_u max/d = 0.46$

$M = 0.36*(x_u max/d)*(1-(0.42*(x_u max/d))*bd^2 fck$

$d_{req} =$ 101.95 mm

$d_{pro} =$ 197.00 mm

$d_{prov} > d_{req}$

A. Bottom reinforcement

1) Longitudinal Reinforcement

M_u limit = 0.87*fy*Ast*d*(1-(Ast*fy)/(bdfck))

$48.6*10^6$ =0.87*500*Ast*209(1-(Ast*500)/(1000*209*35))

$Ast_{req} = 555.66\ mm^2$

Provide 12 mm dia of 150 mm spacing

$Ast_{prov} = 748.8\ mm^2$

2) Transverse Reinforcement

M_u limit = 0.87*fy*Ast*d*(1-(Ast*fy)/(bdfck))

$36.9*10^6$ =0.87*500*Ast*197(1-(Ast*500)/(1000*197*35))

$Ast_{req} = 444.94\ mm^2$

Provide 12 mm dia of 150 mm spacing

$Ast_{prov} = 748.8\ mm^2$

B. Top Reinforcement

1) Longitudinal Reinforcement

M_u limit = 0.87*fy*Ast*d*(1-(Ast*fy)/(bdfck))

$7.53*10^6$ =0.87*500*Ast*209(1-(Ast*500)/(1000*209*35))

$Ast_{req} = 83.29\ mm^2$

Provide 12 mm dia of 150 mm spacing

$Ast_{prov} = 748.8\ mm^2$

2) Transverse Reinforcement

M_u limit = 0.87*fy*Ast*d*(1-(Ast*fy)/(bdfck))

$28*10^6$ =0.87*500*Ast*197(1-(Ast*500)/(1000*197*35))

$Ast_{req} = 334.86\ mm^2$

Provide 12 mm dia of 150 mm spacing

$Ast_{prov} = 748.8\ mm^2$

Figure 14 shows the longitudinal and transverse reinforcement of the track slab.

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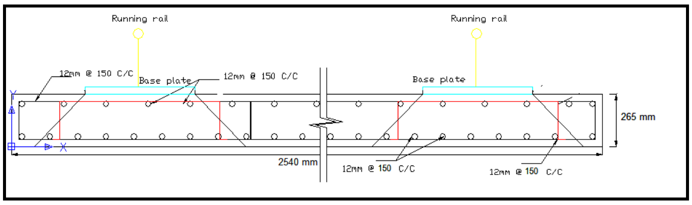

Fig. 14 Reinforcement details of track slab

V. DISCUSSION

Railroad industry is looking for a stronger track structure than the standard ballasted track system. The track slab system overcomes most of the disadvantages that appears in the ballasted system. It greatly increases the life cycle of the track. Analysis and design is very important to the success of any track structure. In the track system, temperature effect plays the major role and it gives greater impact in design moments. As per IS-456 the slab is designed as a beam element and the reinforcement details are explained.

VI. CONCLUSION

The ballastless track slab will lead to safer and swifter railway transportation compared to ballasted tracks. Analysis of track slab can be done with STAAD Pro. 2D elements which will be better in modeling and analysis running time compared to 3D solid elements. Mesh adaptation in plate element gives appropriate results at all required positions. Finer meshes result in accuracy of moment contours. Temperature effect is giving major impact in the design moments. As per IS 456:2000 this can be designed as beam element. Longitudinal and Transverse reinforcement at both top and bottom to adverse hogging and sagging effect respectively is arrived as 12 mm diameter bars at 150 mm C/C spacing.

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